Far-Infrared Imaging Spectroscopy with SAFIRE on SOFIA

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ABSTRACT

The Submillimeter and Far-InfraRed Experiment (SAFIRE) on the SOFIA airborne observatory is an imaging Fabry-Perot spectrometer operating at wavelengths between 100µm and 700µm. SAFIRE's key science goal is to investigate line emission in galaxies at wavelengths not visible from the ground, and to map the variation in this line emission in nearby galaxies. SOFIA will fly at an altitude where the atmosphere is mostly transparent, permitting SAFIRE to achieve a high point source sensitivity at most wavelengths. With a field of view of 160''x320'' at a spectral resolution of ~200km/s, when SAFIRE achieved first light in 2006, it will add substantial capability to the first light instrument complement of SOFIA. SAFIRE's top priority observations will be to measure emission lines in the Galactic center, to map emission lines in nearby galaxies, and to understand the physics of the cores of ultraluminous galaxies from the local region to the high redshift universe through far-infrared fine-structure line emission.

Keywords: bolometer array, transition edge sensor, superconducting multiplexer, SQUID multiplexer, SOFIA

1. INTRODUCTION

The Submillimeter and Far-InfraRed Experiment (SAFIRE) on the SOFIA airborne observatory is designed to be a wide-field imaging spectrometer with moderate spectral resolving power. It will achieve a resolution of about 200km/s, continuously tunable over the 100µm-700µm range. In this paper, we describe the highest priority science projects for SAFIRE which have helped motivate the design of the instrument, discuss the design in broad terms, and predict the performance of the SAFIRE instrument.

2. SCIENCE MOTIVATION

SAFIRE is envisioned as a wide-field spectrometer for measuring line emission from galaxies, specifically concentrating on the far-infrared (100µm-300µm) atomic fine-structure lines (both locally and redshifted) and on submillimeter lines (300µm-650µm) which are not easily accessible from ground-based facilities. It will be a powerful tool for studying such topics as:

- Powering of Ultraluminous Infrared Galaxies
- ISM cooling traced by FIR fine structure lines
- Evolution of Matter in Universe
- Diagnostics of Active Galactic Nuclei
- Star formation in the Galaxy
- Star formation out to high redshifts

SAFIRE's unique capabilities enable a wide variety of science goals. Some high level initial science projects can be chosen even at this point, several years before SAFIRE's first light. Since the results of the ISO satellite, it has become very important to be able to detect redshifted CII (158µm) from ULIRGs such as Arp220 or Mrk231, which SAFIRE can do out to z~1. At longer wavelengths (λ>160µm) where ISO was not as effective and where ground-based telescopes cannot observe, SAFIRE will be an important instrument for characterizing the line emission from a variety of galaxies. Finally, projects which require large area imaging spectroscopy – for instance, the study of the Galactic center, where measuring the spatial structure of emission lines will be revealing – are ideal for SAFIRE's large detector array.

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SAFIRE can be compared to other SOFIA first light instruments on the basis of its wavelength coverage, spectral resolution, and imaging area. A spectral resolution well-suited to galaxies at λ>200μm is not covered by any other instrument (Figure 1). SAFIRE also has a very large instantaneous field-of-view (Figure 2), which is designed to enable it to map nearby galaxies quickly and efficiently. Simultaneous imaging has the obvious benefit of increasing the speed of observation, and additionally has the benefit of reducing the systematic errors associated with raster and jiggle mapping.

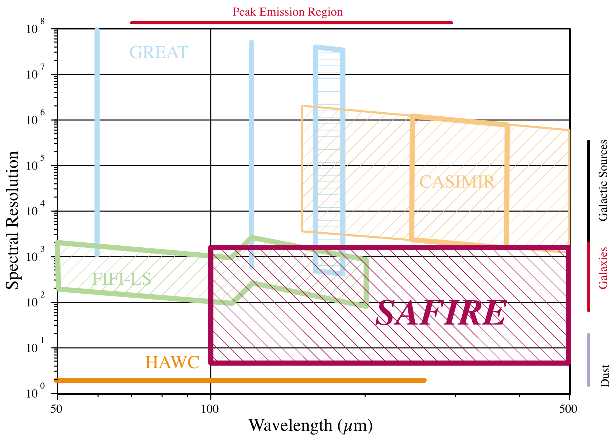

Figure 1. Spectral resolution of SOFIA first light instruments at wavelengths longer than 50μm.

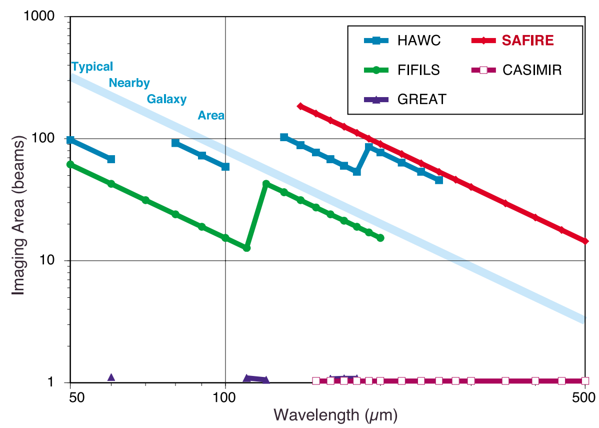

Figure 2. Areal coverage of SOFIA first light instruments, expressed as the number of beams imaged instantaneously.

3. SENSITIVITY LIMITATIONS

The background power on SOFIA is largely determined by the emissivity of the atmosphere, shown in Figure 3. This can be translated into an atmospheric photon noise equivalent power (NEP), as shown in Figure 4. The SAFIRE detectors will need to achieve a phonon and Johnson noise sum of $<3\cdot10^{-18}$ W/√Hz in order to be background-limited, and must be able to absorb up to ~0.3pW in order to avoid saturation. This puts a stiff requirement on the dynamic range of the bolometers, in that the ratio of maximum power detected to the minimum power detectable in unity bandwidth is about 10^5. At a fixed spectral resolving power of 1000, the noise equivalent flux density (NEFD) and line sensitivity can be calculated (Figures 5 and 6). A typical NEFD is of order 1Jy/√Hz, while the line sensitivities are typically better than 10^{-17} W/m^2 at the 5σ level in one hour of observation. For comparison, emission lines from many interesting galaxies – including the fine-structure lines from luminous galaxies out to z~0.1 – are of brightnesses of ~10^{-16} W/m^2.

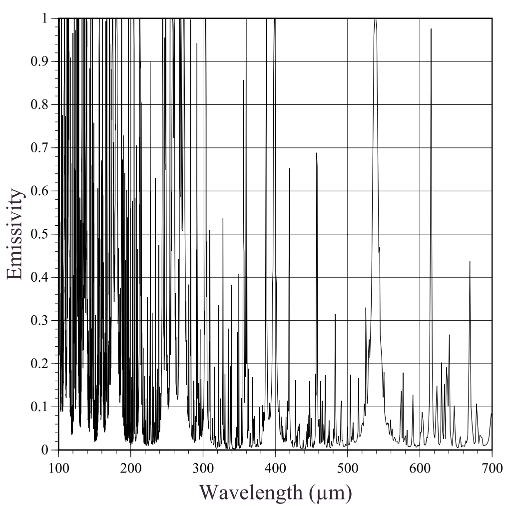

Figure 3. Atmospheric emission from SOFIA altitudes, assuming 5μm precipitable water vapor[1]

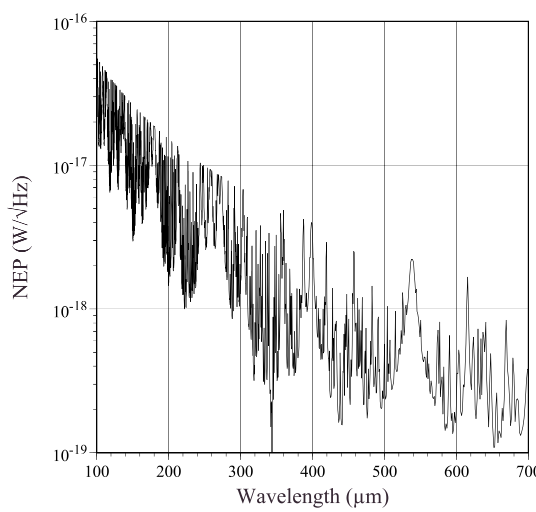

Figure 4. Photon noise equivalent power from the emission shown in Figure 1.

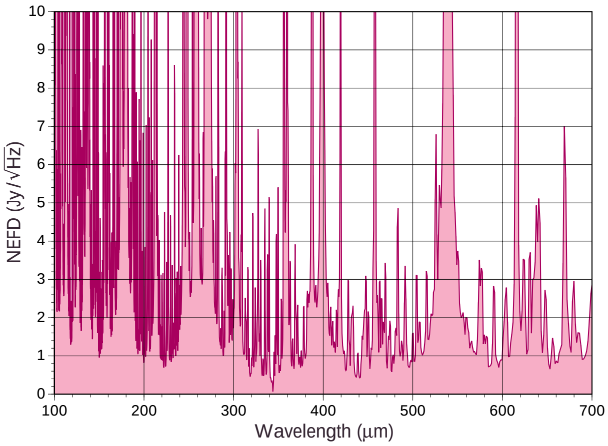

Figure 5. Atmospheric NEFD from SOFIA altitudes, assuming 5μm precipitable water vapor

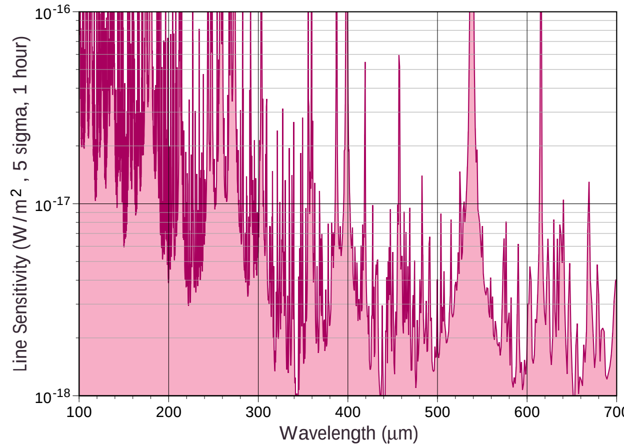

Figure 6. Point source line sensitivity at the 5σ level after one hour of observation.

4. WAVELENGTH COVERAGE , SPECTRAL RESOLUTION, AND FIELD OF VIEW

SAFIRE achieves its high spectral resolution using a double Fabry-Perot design, shown in Figure 7. One of the design features is that the use of lenses and flat mirrors reduces the aberrations induced by large field angles in off-axis systems. Stray light is reduced by means of a set of stops at the entrance to the 4.2K-cooled region, which is a light-tight enclosure. All the optical elements are mounted on a removable plate, to allow convenient room-temperature assembly and alignment. The only exceptions to this are a speeding lens mounted at 77K and the detector array, mounted on a 1.3K stage. The detectors are superconducting transition edge sensor bolometers operated at ~200mK, which are described elsewhere[2].

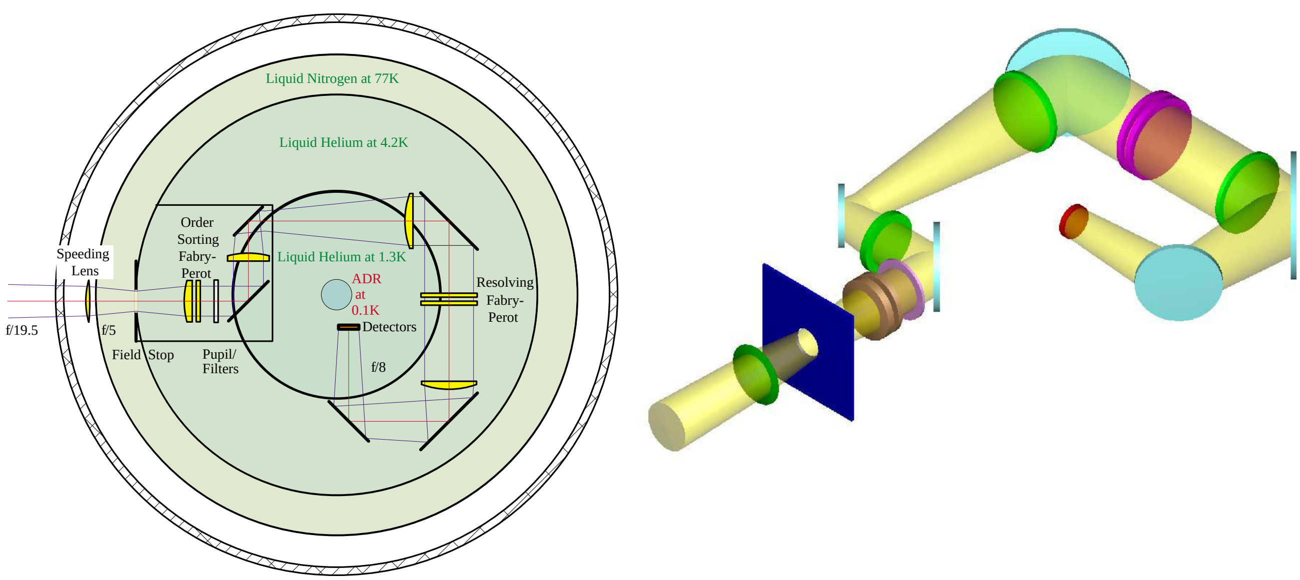

Figure 7. SAFIRE optics design. (L) Schematic layout showing the placement of components in the cryostat. (R) Simplified rendering of the optical path.

A double Fabry-Perot is a straightforward optical system, in which a low-resolution etalon provides order-sorting for a high-resolution etalon. Because of the broad tuning range required to cover 100-700μm, a filter wheel with six settings provides order sorting for the low-resolution etalon. The resultant spectral resolution is shown in Figure 8. A standard set of 6 filters is used to provide the resolutions of 150-300km/s, completely covering the 100µm-700µm range. For higher spectral resolution, a set of filters for certain atomic fine-structure lines can be installed in this filter wheel, for the CII line at 158µm, the OI line at 145µm, and the NII lines at 122 and 205µm. These filters would permit observations at resolutions of ~100km/s, more suited to sources in our own galaxy.

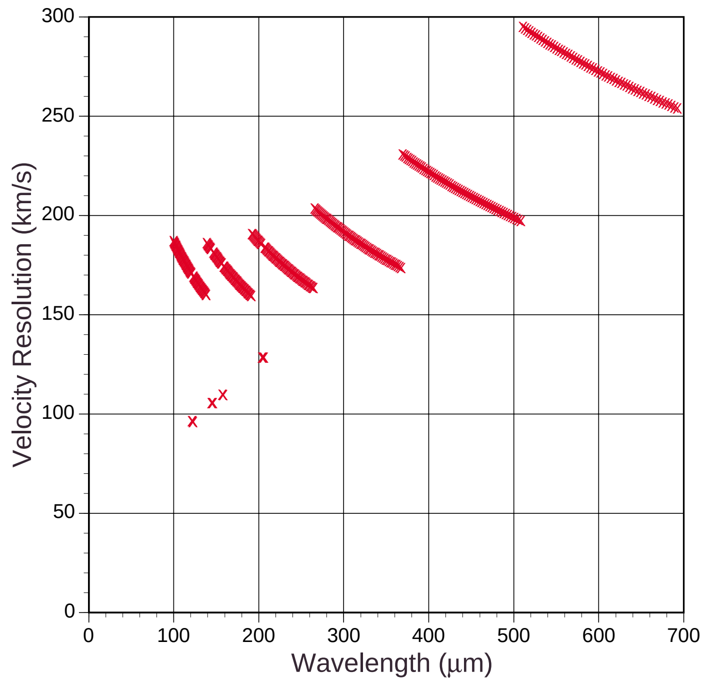

Figure 8. Spectral resolution vs. wavelength. A standard set of 6 filters is used to provide resolutions of 150–300km/s over a wide band, while a separate set of 4 filters provide resolutions of ~100km/s for certain lines.

On SOFIA, a large field of view is available with diffraction-limited performance in the far-infrared. The spatial resolution at 200µm is 20''. It is therefore reasonable to set the plate scale in the focal plane to 10'' per pixel. We are developing a 16x32 detector array for this purpose using multiplexed superconducting transition edge sensor bolometers[2]. The field of view is then 160"x320".

The SAFIRE instrument is designed to be a highly modular system (Figure 9). This permits the assembly and testing of each component separately, which is necessary for programmatic reasons. SAFIRE is being developed slowly, with components being assembled serially by a limited workforce. As these items are completed, they are held until needed for later integration and testing.

SAFIRE's detectors are the most technologically advanced component, and have received much of the attention to date because of their relatively high development needs. A prototype instrument for the demonstration of these detectors is described elsewhere[3,4]. The detectors are cooled by an adiabatic demagnetization refrigerator built for SAFIRE, and similar to that used in the HAWC instrument on SOFIA[5,6]. In order to modularize these two components for testing, an insertable cryostat has been fabricated at the Goddard Space Flight Center. This cryostat can be installed in the SAFIRE cryostat, which is a custom-built LN_2/LHe dewar from Precision Cryogenics[7]. An optics plate can be mounted in this cryostat on the 4.2K surface, as described above. The two Fabry-Perot mechanisms and the filter wheel, together with other optical components and baffling, are mounted on this optics plate. A light-tight shield surrounds the optics plate. Almost all the analog portions of the detector electronics are mounted on the insertable cryostat, in order to keep them within a single electrically-shielded environment; digital electronics are mounted in a chassis on the side of the cryostat. Finally, software for the commanding of the instrument, data acquisition and display, and housekeeping information and control is being developed. The software, called Instrument Remote Control (IRC[8]), is designed to be a platform-independent, extensible, modular environment usable for many SOFIA and related instruments.

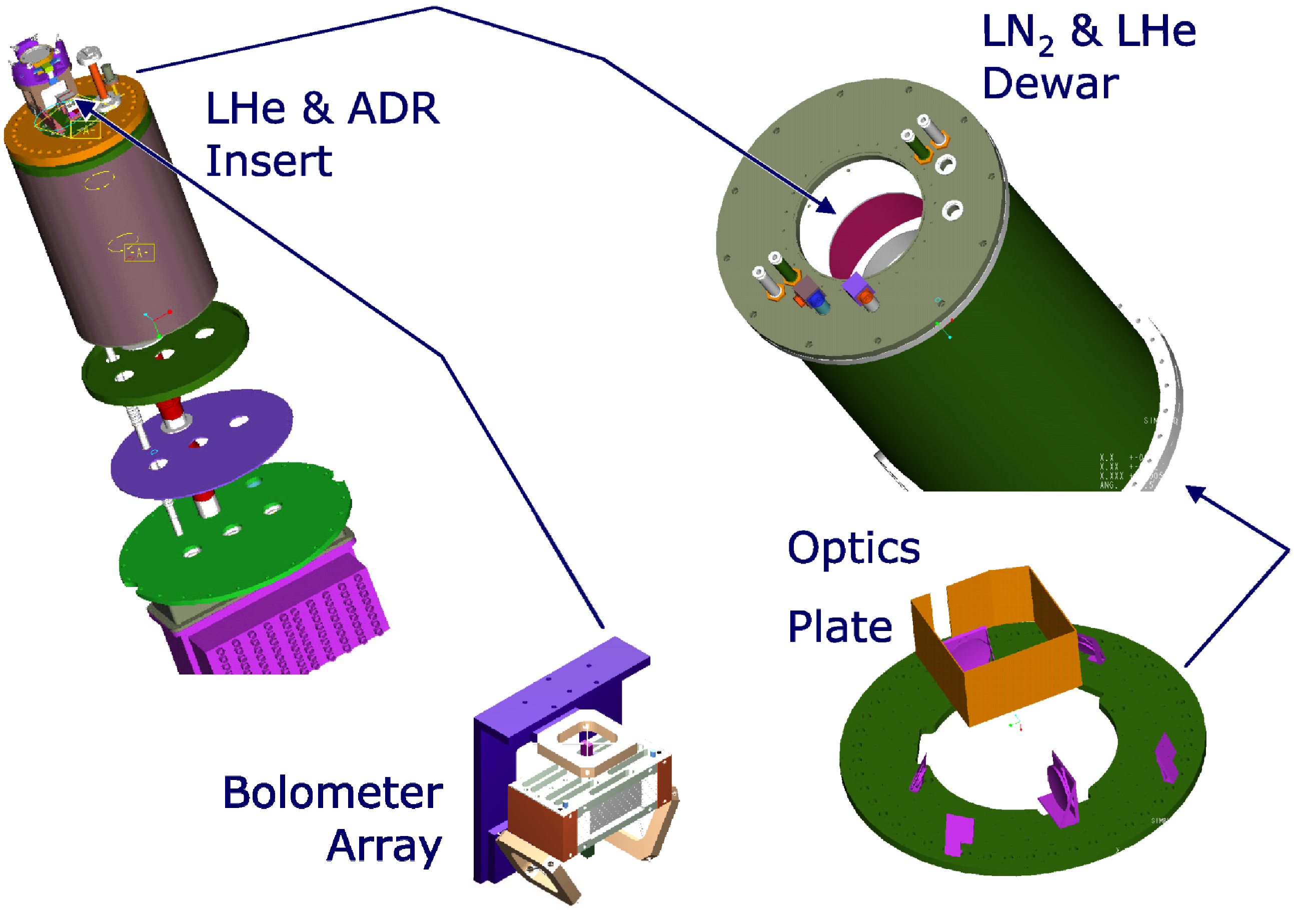

Figure 9. The major portions of the SAFIRE instrument; not shown explicitly are optical mechanisms, electronics, and software.

5. SCIENCE INVESTIGATIONS

5.1 Far-Infrared Line Emission

Many fine-structure and molecular-transition lines serve as probes of the physical properties of the ISM of the Milky Way and other galaxies. One example of this is shown by the COBE/FIRAS average line spectrum of our galaxy, which shows several important lines (Figure 10)[9]. As an example, we list below several far-infrared lines and the physical investigations which can be conducted by observing them.

- OI lines probe the physical conditions of gas in PDRs.
- NII lines trace the warm ionized medium.
- CII line traces PDRs, atomic clouds, and warm ionized medium.
- NII (with NIII) gives the effective temperature of stellar or AGN UV radiation fields.
- SiI line indicates the presence of dissociative J-shocks.
- High-*J* CO rotational lines trace shocked gas found in warm dense gas of PDRs.
- OH lines trace shocked gas in cool dense gas.
- OH, CH, and NH_3 together constrain molecular cloud chemistry.
- CI traces star formation, atomic clouds.

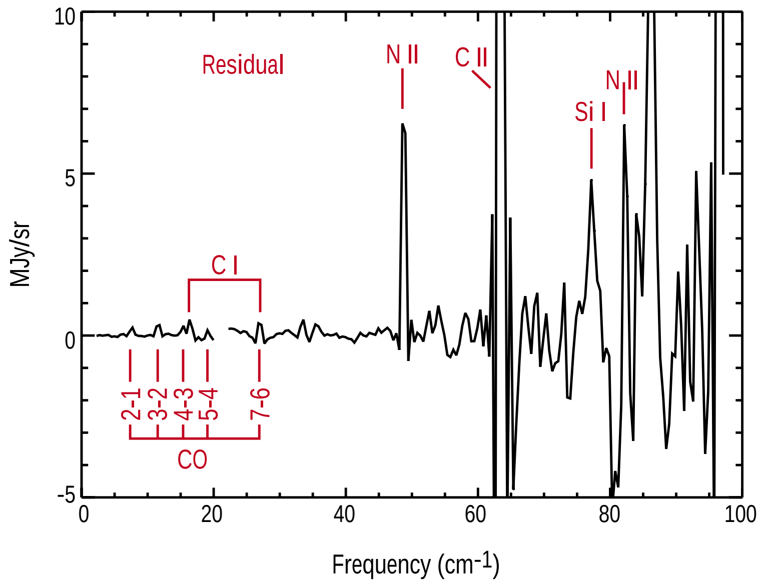

Figure 10. COBE/FIRAS average line spectrum of the Milky Way, covering the SAFIRE bands (15-100 cm^{-1}) and showing the stronger lines.

The brightest emission lines from star forming galaxies are the fine-structure lines of common species: CII at 158µm, OI at 145µm, and NII at 122µm and 205µm. These lines dominate the cooling of several phases of the ISM, which comprise much of the mass. These lines also trace a variety of source types, including HII regions, atomic clouds, and photon dominated regions. These lines can be used as a diagnostic of the interstellar radiation field (both its hardness and its intensity) and can probe the density, mass, and metallicity of the ISM. Of particular note among the fine-structure lines is the brightest, the 158µm CII line, which typically accounts for between 0.1 and 1% of the total far-IR luminosity of star forming Galaxies[10]. Furthermore, several bright shorter wavelength lines will be visible by SAFIRE when redshifted; these include OI 63µm (~50% CII flux); OIII 52µm and 88µm (~50% CII flux); NII 122µm (~20% CII flux); NII 205µm (~10% CII flux).

5.2 Galactic Center

The Galactic center region is an interesting laboratory of physics, showing a broad range of phenomena in the interstellar medium at angular and temperature scales relevant to investigation with SAFIRE on SOFIA. SAFIRE can map the entire thermal and nonthermal arches region in a wide variety of spectral lines and at high angular resolution (Figure 11). One outstanding question is simple: where are the stars? While it is clear that the thermal arches are excited by stellar radiation, it is not clear where these stars are. Mapping in CII, OI, NII, and mid-J CO lines delineates PDRs, ionized, and molecular gas, and locates excitation gradients, thereby locating the sources of excitation. The Sickle is also heated by starlight, but its morphology is distorted by the strong magnetic fields of non-thermal filaments. The ionized surfaces of molecular clouds may be the electron source for these non-thermal filaments. One can expect shock excited lines (e.g. mid- to high-*J* CO and HCN) there.

SAFIRE's field of view is large enough to take a snapshot of the circumnuclear ring. Its spectral coverage will allow a variety of investigations. One possible project is to determine the mass and physical size of the circumnuclear ring. One approach is to use the CI line ratios, which trace gas column density and temperature, but are insensitive to gas density. It is estimated that this gas only remains in the ring for ~10^4 years, so where is the gas reservoir that replenishes the ring? SAFIRE can observe the CII 158µm and OI 145µm lines, which trace gas excitation and kinematics at high spatial resolution over broad regions. What is the excitation mechanism for the bright molecular line emission from the ring: radiation from stellar cluster, or shocks? Mid- and high-*J* CO line ratios trace excitation of molecular gas; shock excited material will be broadly distributed, whereas UV excitation should be seen only near the exciting stars. Another diagnostic is to observe the OH 163µm line, which is radiatively pumped; when compared with CO, this measurement can decouple shock from UV excitation.

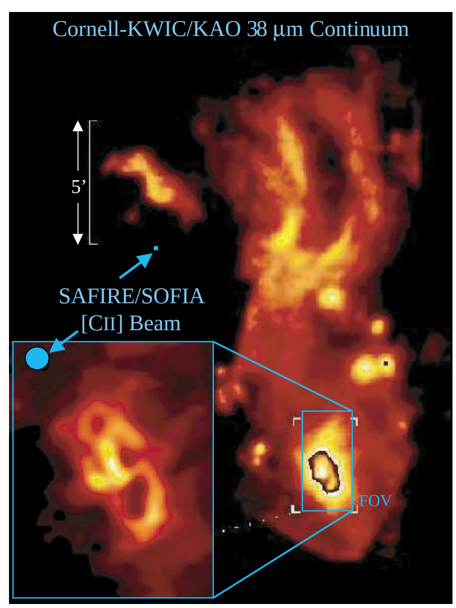

Figure 11. KAO/KWIC 38µm image of the Galactic center, with inset enlargement of the circumnuclear ring.

5.3 Local & Normal galaxies

As a diagnostic of local galaxies, SAFIRE’s great strength is in its large instantaneous spatial coverage. A nearby galaxy such as M83 is of order 7’ in diameter, but can be imaged in only a few SAFIRE fields-of-view. A map of M83 made in the CII 158µm lines using the FIFI instrument aboard the KAO[11] is shown in Figure 12. Using SAFIRE on SOFIA, the angular resolution is about 3 times better, sufficient to resolve the spiral structure at very high contrast ratios. Furthermore, the sensitivity of SAFIRE will allow the KAO map to be duplicated at the SOFIA resolution in about one hour of observing time. Bright sources such as Cen A[12] can be observed at a signal-to-noise of ~10 with a single pointing lasting only seconds.

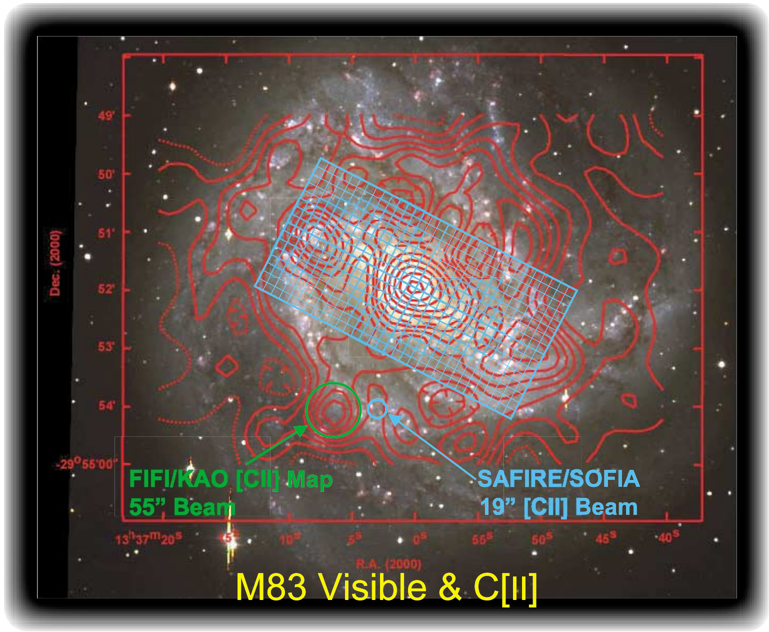

Figure 12. Observations of CII 158µm emission made by the FIFI instrument on the KAO (contours) overlaid on a visible image. SAFIRE’s array footprint is shown, oriented along the major axis of the galaxy. The angular resolution of SAFIRE will permit the separation of nuclear, arm, and interarm components of emission.

An image does not represent sufficiently the wealth of information acquired by an imaging spectrometer. Consider instead the nearby starburst galaxy M82. Four tunings of the SAFIRE Fabry-Perot, spaced by 150km/s, results in the image stack shown at right in Figure 13. The central source of ~1’ in diameter can be seen to move across the field, showing the dynamics of the galaxy. If we choose one of the brightest regions and slew the Fabry-Perot over a broad range, we can build up a complete spectrum of that position (and all others in the field of view). A simulation of this is shown at left in Figure 13.

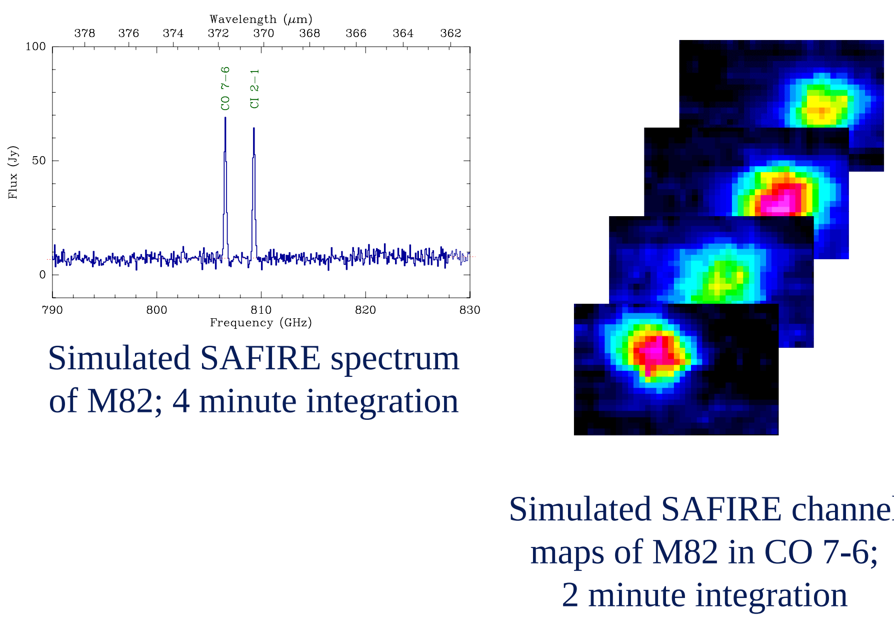

Figure 13. Simulations of SAFIRE 3D observations of M82. (Left) cut through the data cube at one spatially averaged region, showing the spectrum of that area. (Right) Stack of images separated by 150km/s (approximate resolution of SAFIRE) showing the motion of the galaxy. SAFIRE can detect M82 extremely quickly and much fainter sources with reasonable integrations.

5.4 Diagnostics of ULIRGs

In the far-infrared, Ultraluminous Infrared Galaxies (ULIRGs) often have prominent fine-structure lines. These lines can trace the radiation fields in the cores of ULIRGs, measure the gas properties, and probe abundances. Typically, these lines dominate the gas cooling. However, in the prototypical ULIRG Arp220, which has very strong molecular emission, the 158µm line of ionized carbon is an order of magnitude weaker than expected. By contrast, Arp299, which is also a ULIRG, has a bright CII line. In fact, less than half of the ULIRGs have severe CII deficits, despite being similar in luminosity. It can be seen that the far-infrared spectrum of such galaxies can differ substantially[13] (Figure 14). ISO's sensitivity did not permit it to measure a large sample of ULIRGs; it was also not able to detect line emission from sources at even quite small redshifts. SIRTF does not have spectroscopic capability in this wavelength region. SAFIRE will be the most sensitive instrument for measuring the wealth of far-infrared fine-structure lines until Herschel becomes available.

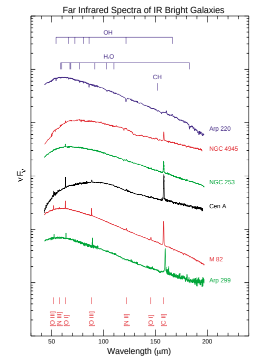

Figure 14. ULIRG spectra from ISO.

5.5 High redshift

The far-infrared continuum is a good diagnostic of the total luminosity of dusty galaxies, and has been measured out to high redshifts by ground-based instruments[14]. SOFIA's facility camera, HAWC, will achieve very high point source sensitivity across the far-infrared, and will detect large numbers of galaxies at redshifts out to z~3[15]. Since strong CII emission is often associated with star formation, SAFIRE can conduct a companion survey of CII in the distant universe. SAFIRE's wavelength range covers z=0 to z=3.4, which encompasses the great change in star formation rate per unit in co-moving volume. Figure 15 shows the measured star formation rate density compared with several models[16], highlighting SAFIRE's ability to measure this parameter. This will help to provide an answer to two important questions: What powers high redshift, dusty galaxies? How strong are starbursts in the early universe?

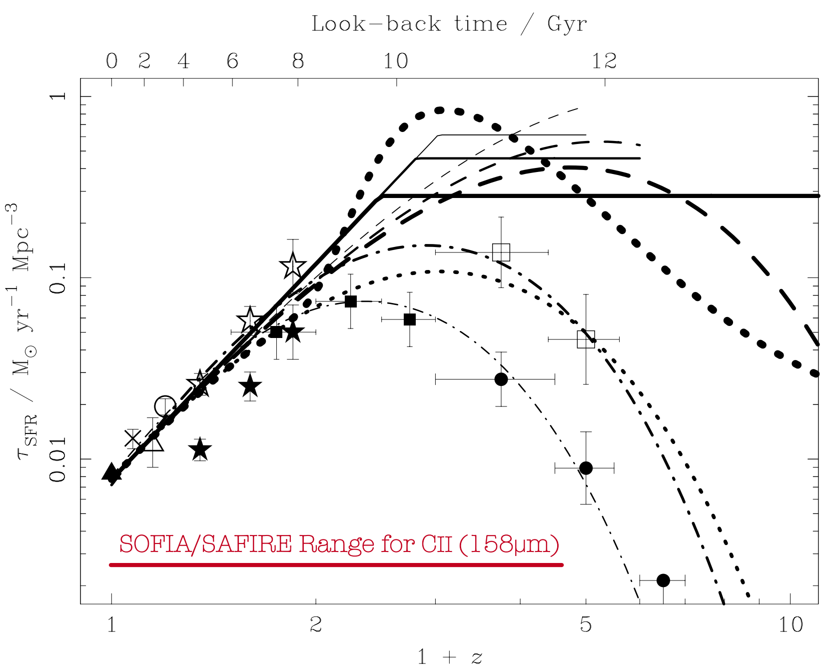

Figure 15. Star formation rate density measurements and models, from Blain et al. (1999)[16].

In the case of surveying nearby galaxies, there is much to learn about the CII emission: there is a tendency for higher luminosity sources to have a smaller CII line to far-infrared continuum ratio[17]. This change in line ratio is a physical diagnostic – to first order, the ratio reflects the strength of the ambient interstellar radiation field, G_0. SAFIRE can trace this line in ULIRGs out to z>0.3 with integration times of about one hour. This is shown schematically in Figure 16. There is also a trend of changing CII luminosity as a function of the far-infrared color (and hence temperature) of galaxies; SAFIRE can measure this variation in normal galaxies out to z~0.2 and in ULIRGs out to z~3 (Figure 17).

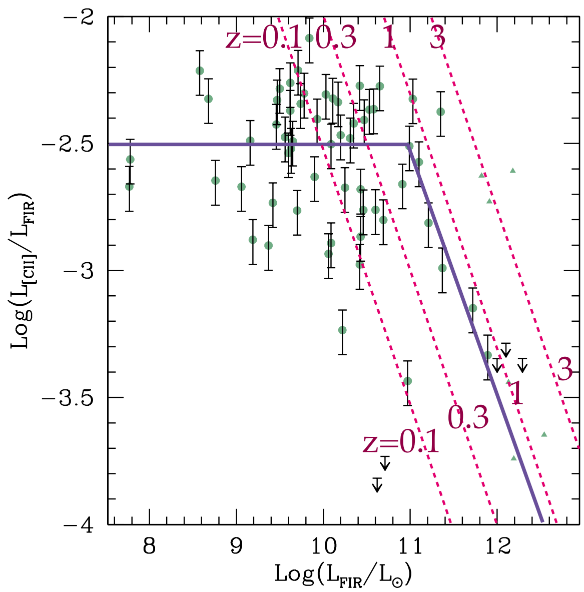

Figure 16. Fractional luminosity of the CII (158μm) emission of galaxies from Malhotra et al (2001)[17]. An approximate fit is shown, along with four lines indicating SAFIRE's one hour sensitivity limit (1σ) at z=0.1, 0.3, 1, and 3.

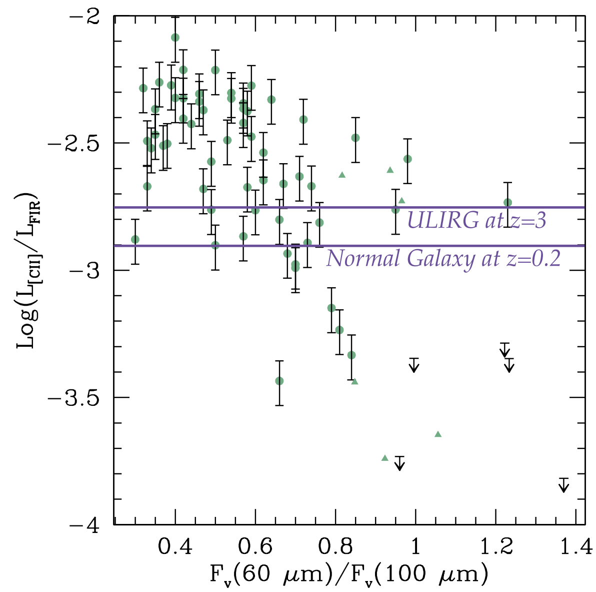

Figure 17. Fractional CII luminosity as in Figure 16, but plotted against the far-infrared color. The horizontal lines indicate the sensitivity of SAFIRE (1σ in one hour) to ULIRGs at z=3 (also LIRGs at z=0.5) and a normal galaxy at z-0.2.

5.6 Complementarity to other facilities

Since SAFIRE will achieve first light on SOFIA in 2006, it will coexist immediately with SIRTF and, later, with Herschel. It is therefore useful to consider how SAFIRE adds scientific capability for the astronomical community.

SIRTF will have supreme sensitivity, but is limited by a relatively small 85cm aperture and a cutoff wavelength (in broadband imaging alone) at 170μm. SAFIRE will have the benefit of SOFIA's 2.5m aperture, but will operate at longer wavelengths, so the diffraction-limited resolution will be comparable. SAFIRE has both imaging and spectroscopic capability, so serves as a strong diagnostic tool for studying sources discovered by SIRTF. Furthermore, SAFIRE's spatial and spectral resolution are comparable to that of SIRTF/IRS, so that SAFIRE can study highly redshifted sources and compare that data with SIRTF's observations of nearby sources.

Herschel is a warm telescope like SOFIA, but is larger (3.5m) and does not have any atmospheric absorption lines (which, though modest at SOFIA altitudes, is not negligible). SAFIRE provides a useful capability when compared to Herschel's instrument complement. Its spectral resolution is finer that SPIRE's, while the two instruments cover similar wavelength ranges. SAFIRE has a spectral coverage and areal coverage greater that HIFI, permitting more flexibility and more rapid mapping of extended bright regions. SAFIRE's capabilities are similar to PACS, but SAFIRE's coverage extends to longer wavelengths; this will allow SAFIRE to extend PACS studies of galaxies out to higher redshifts.

6. SUMMARY

SAFIRE fills a unique role for SOFIA, and its capabilities enable many science projects. Some highlights of enabled investigations include studies of the Galactic center, the study the spatial distribution of lines in nearby galaxies, the study of distant galaxies through their fine-structure line emission, and studies of ionized carbon emission from a variety of sources. Additionally, SAFIRE is a platform to develop technologies; superconducting bolometer arrays and flexible instrument control software are two notable examples. SAFIRE is scheduled to acquire first light on SOFIA in 2006.

REFERENCES

1. Grossman, E.N. 1989, "AT-Atmospheric Transmission Software User's Manual, v1.5", Airhead Software Co., 2069 Bluff St., Boulder, CO 80302
2. Benford, D.J., Voellmer, G.M., Chervenak, J.A., Irwin, K.D., Moseley, S.H., Shafer, R.A. & Staguhn, J.G. 2002, Proc. SPIE #4857, in press; *"Design and Fabrication of a Two-Dimensional Superconducting Bolometer Array for SAFIRE"*
3. Benford, D.J. et al. 2001, AIP Conference proceedings #605, "Low Temperature Detectors", F.S. Porter et al., eds., pp.589-592, *"First Astronomical Use of Multiplexed Transition Edge Bolometers"*
4. Staguhn, J.G. et al. 2002, Proc. SPIE #4855, in press; *"Astronomical Demonstration of Superconducting Bolometer Arrays"*
5. Tuttle, J. et al. 2001, Cryogenics #41, pp.781-787; *"The HAWC and SAFIRE adiabatic demagnetization refrigerators"*
6. Voellmer, G.M. & Jackson, M.L. 2002, Proc. SPIE #4850, in press; *"Kinematic Kevlar Suspension System for the HAWC and SAFIRE ADR Salt Pills"*
7. Precision Cryogenic Systems, Inc., 7804 Rockville Rd., Indianapolis, IN 46214; 317.273.2800
8. Ames, T.J. & Case, L. 2002, these proceedings; *"Distributed Framework for Dynamic Telescope and Instrument Control"*
9. Bennett, C.L. et al. 1994, ApJ #434, pp.587-598; *"Morphology of the interstellar cooling lines detected by COBE"*
10. Stacey, G. J., Geis, N., Genzel, R., Lugten, J. B., Poglitsch, A., Sternberg, A. & Townes, C. H. 1999, ApJ #373, pp.423-444; *"The 158 micron forbidden C II line - A measure of global star formation activity in galaxies"*
11. Stacey, G.J. et al. 1999, in ESA-SP #427, "The Universe as Seen by ISO"; *"Far-infrared spectroscopic images of M83"*
12. Madden, S.C., Geis, N., Townes, C.H., Genzel, R., Hermann, F., Poglitsch, A. & Stacey, G.J. 1995, ASP Proc. Vol 73, pp.181-184; *"Extragalactic diffuse (C II) emission"*
13. Fischer, J. et al. 1999, Ap&SS v.266, pp.91-98; *"ISO Far-IR Spectroscopy of IR-Bright Galaxies and ULIRGs"*
14. Benford, D.J., Cox, P., Omont, A., Phillips, T.G. & McMahon, R.G. 1999, ApJ 518, L65; *"350μm Dust Emission from High-Redshift Objects"*
15. Harper, D.A. et al. 2000, Proc. SPIE #4014, pp.43-53; *"HAWC:A Far-Infrared Camera for SOFIA"*
16. Blain, A.W., Smail, I., Ivison, R.J. & Kneib, J.-P. 1999, MNRAS v.302, p.632; *"The History of Star Formation in Dusty Galaxies"*
17. Malhotra, S. et al. 2002, ApJ #561, pp.766-786; *"Far-Infrared Spectroscopy of Normal Galaxies: Physical Conditions in the Interstellar Medium"*